

Massive star feedback – from the first stars to the present

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Abstract. The amount of mass loss is of fundamental importance to the lives and deaths of very massive stars, their input of chemical elements and momentum into the interstellar and intergalactic media, as well as their emitted ionizing radiation. I review mass-loss predictions for hot massive stars as a function of metal content for groups of OB stars, Luminous Blue Variables, and Wolf-Rayet stars. Although it is found that the predicted mass-loss rates drop steeply with decreasing metal content ($M \sim Z^{0.7-0.85}$), I highlight two pieces of physics that are often overlooked: (i) mass-loss predictions for massive stars approaching the Eddington limit, and for (ii) stars that have enriched their own atmospheres with primary elements such as carbon. Both of these effects may significantly boost the mass-loss rates of the first stars – relevant for the reionization of the Universe, and a potential pre-enrichment of the intergalactic medium – prior to the first supernova explosions.

1. Introduction: stellar cosmology

Over the last couple of years, we have witnessed a large increase in the interest in hot luminous stars. The reasons for this are manifold. Some of the eye-catchers have been the identification of long-duration gamma-ray bursts (GRBs) with supernova explosions (Galama et al. 1998, Hjorth et al. 2003) as well as massive star formation at high redshift (Bloom et al. 2002). In addition, the impressive numerical simulations regarding the formation of the first stars at zero metallicity (Population III) – widely believed to be very massive stars (VMS) with $M \sim 100M_{\odot}$ (Abel et al. 2002, Bromm et al. 1999) – have triggered increased attention into the workings of massive stars at low metallicity (Z).

Aside from these relatively recent developments, hot stars with their strong winds have continuously been at the forefront of astrophysical research. This is largely due to their roles in shaping their environments, by releasing large amounts of mechanical energy via their winds and supernovae, as well as via their vast quantities of ionizing radiation.

It is the *amount* of mass loss that lies at the heart of massive star feedback, as it is this very quantity that determines: (i) the evolution of massive stars towards their final phases, including their ultimate fate, (ii) the density structure of the atmosphere, which, in turn sets the terminal wind velocity, and the wind energy release into the interstellar medium (ISM), and finally (iii) the hardness of the ionizing radiation field (see Gabler et al. 1989).

Now that the high-redshift Universe has become increasingly more accessible, both with wonderful detections of the integrated light of massive stars

in star-bursting galaxies at $z > 6$ (e.g. Bunker et al. 2004), as well as with fingerprints of *individual* massive stars via their associated GRBs (for instance with SWIFT), it is critical to understand the nature of massive stars and their feedback as a function of metal content.

It has been known for many years, that mass-loss uncertainties as small as a factor of two are able to completely change massive star model output (Meynet et al. 1994), but the uncertainties relating to mass loss at very low ($Z/Z_{\odot} \sim 10^{-2}$) and extremely low ($Z/Z_{\odot} \lesssim 10^{-3}$) metallicity are highly uncertain and could easily amount to factors of thousands.

Properly understanding and accurately *predicting* the mass-loss rate as a function of metal content is therefore of prime importance for reliably assessing the direct role of massive star winds in pre-enriching the intergalactic medium (IGM) at early epochs, their intricate role in determining the evolution of Population III stars to their final explosions, and the amount of ionizing radiation that may have significantly contributed to the reionization of the Universe.

For these reasons, mass-loss predictions as a function of metallicity are at the heart of “Stellar Cosmology”. Since individual massive star winds are not observable at metallicities below $Z/Z_{\odot} \sim 10^{-1.5}$, we must rely on a comprehensive modelling procedure to allow for a quantitative comparison with observational analyses of stars in the local Universe, as well as a robust method for extrapolating these predictions into the extremely low Z ($Z/Z_{\odot} \lesssim -3$) domain, where we can no longer observe stellar winds *directly*.

In the next section, I describe the physical process of radiation pressure on spectral lines, widely accepted to drive massive star winds, and continue to introduce two approaches currently in use for predicting mass-loss rates of massive stars, the CAK and Monte Carlo approach, with their pros and cons. In section 3, the successes and remaining challenges of these predictions are described for a range of massive objects comprising OB supergiants, Luminous Blue Variables (LBVs), and Wolf-Rayet (WR) stars, with a prime focus on their metallicity dependence. I finish with a discussion highlighting cosmological implications of these initial results.

2. Two methods to predict hot-star mass-loss rates

Light carries momentum, and it has been known since the 1920s (e.g. Milne 1926) that radiation pressure on spectral lines is able to eject atoms from stars. Nonetheless, it was not until the late 1960s, when sensitive UV mass-loss diagnostics of O star winds became available, that radiation pressure on spectral lines came back into the foreground of astrophysical research.

2.1. The line-driven wind theory and the CAK approach

Lucy & Solomon (1970) were the first to realize that radiation pressure on metal lines, in combination with sharing this momentum with the abundant hydrogen plasma, could drive a continuous outflow from hot luminous stars. The necessary condition for initiating a wind is that the radiative acceleration g_{rad} exceeds gravity, as can be seen in the momentum equation:

$$v \frac{dv}{dr} = - \frac{GM}{R^2} + g_{\text{rad}} \quad (1)$$

where the gas pressure term is neglected. For a more comprehensive review on stellar wind theory, and in particular how the various relevant forces determine a star's mass-loss rate and terminal wind velocity, I refer the reader to Lamers & Cassinelli (1999).

The challenge lies primarily in accurately predicting the g_{rad} term in the equation of motion. For free electrons this is simply the electron opacity, κ_e , times the flux:

$$g_{\text{rad}}^{\text{elec}} = \frac{\kappa_e L}{4\pi r^2 c} \quad (2)$$

However line scattering turns out to be the more dominant contributor to the total radiative force. The reason for this is that although photons and matter are allowed to interact only at very specific frequencies, the two can be made to “resonate” at a wide range of positions in the stellar wind due to the Doppler effect (see reviews by Abbott 1984, Owocki 1994). Historically, the total radiative acceleration in hot star atmospheres is effectively the force due to free electrons *multiplied* by a factor M , the line Force Multiplier introduced by Castor et al. (1975; CAK), for the contribution of strong and weak spectral lines. $M(r, t, dv/dr)$ is a function of distance in the wind r , optical depth t , and velocity gradient, dv/dr . In this formulation the radiative acceleration depends itself on the Newtonian acceleration from the inertia term and the equation of motion (Eq. 1) becomes non-linear (e.g. Lucy 1998). CAK computed this Force Multiplier for an ensemble of carbon III lines in Local Thermodynamic Equilibrium (LTE) and found their $M(t)$ to be a linear function of optical depth, so that they were able to fit this function with two parameters

$$M(t) = k t^{-\alpha} \quad (3)$$

where k and α are the famous CAK force multiplier parameters, k being a measure for the number of lines, and α representing the number of strong to weak lines. Several interesting papers have appeared in the last three decades to extend the line force description (with δ for ionization; Abbott 1982) and to gain a better understanding of the underlying line strength distribution function (Gayley 1995, Puls et al. 2000). These analyses have been helpful to our understanding of the physics of the line driving force. As the line acceleration could simply be fit with two parameters, the equation of motion (Eq. 1) was solved in a relatively straightforward manner, delivering simultaneously the mass-loss rate (\dot{M}) and the terminal wind velocity (v_∞).

It is important to realize that the CAK predictions yielded mass-loss rates of order $10^{-6} M_\odot \text{yr}^{-1}$, a factor of ~ 100 higher than from the original work by Lucy & Solomon (1970), and in good accord with even today's observations, although we now know *a posteriori* that this was somewhat of a coincidence, as the contribution of iron (Fe) to the line force greatly exceeds that of carbon for Galactic Z . Nevertheless, the high mass-loss rates predicted by CAK were pivotal for the realization that hot-star winds are not an observational curiosity, but that they play a fundamental role in the evolution of a massive star.

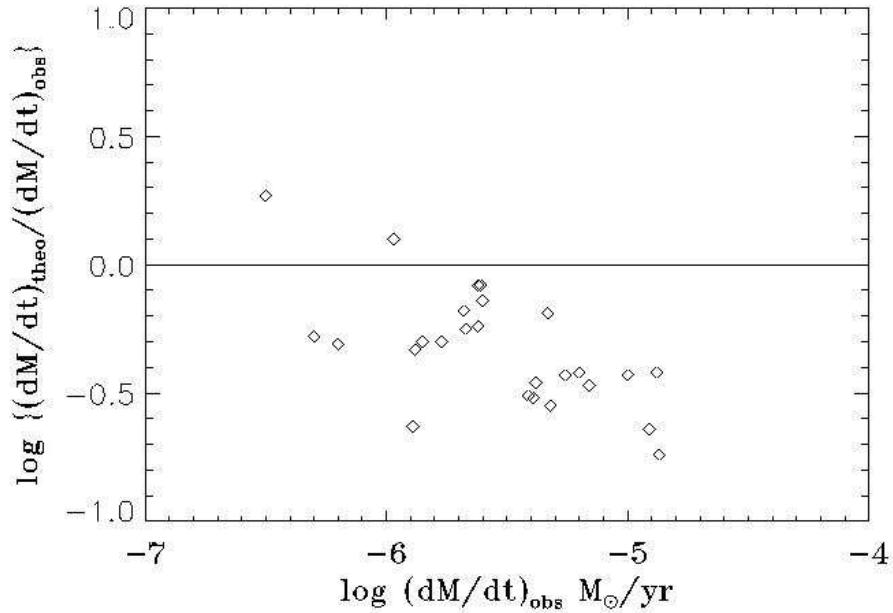


Figure 1. A comparison between the modified-CAK mass-loss predictions from the Munich group and $H\alpha$ mass-loss rates from Lamers & Leitherer (1993) – as a function of the observed mass-loss rate. If modified-CAK theory would be in good agreement with observations, the data-points should scatter around the solid line, however they show a systematic discrepancy, which grows with increasing wind density: the *momentum problem*. The figure is taken from Vink (2000).

Since the time of the original CAK computations, the atomic physics has been massively updated in modern codes and occupation numbers have been computed in non-LTE by the Munich group (Pauldrach et al. 1990), these modified CAK-type predictions have reached better agreement with observational analyses, but have not been able to account for the high-mass loss rates in the denser winds of O supergiants. This is best exemplified by a comparison between the observed mass-loss rates based on the $H\alpha$ equivalent width and modified-CAK predictions from the Munich group in Fig. 1.

2.2. The Monte Carlo method

It was this momentum problem present in dense O winds as well as Wolf-Rayet (WR) winds that led Abbott & Lucy (1985) to develop an entirely new method for predicting the line acceleration via Monte Carlo (MC) radiative transfer simulations. Figure 2 represents a typical Monte Carlo photon that undergoes multiple interactions with the outflowing matter, thereby depositing momentum and energy. The philosophy behind the Abbott & Lucy approach was to *adopt* a β velocity law with an empirically determined v_∞ , and derive reliable mass-loss rates from the energy extracted from the radiation field – properly including

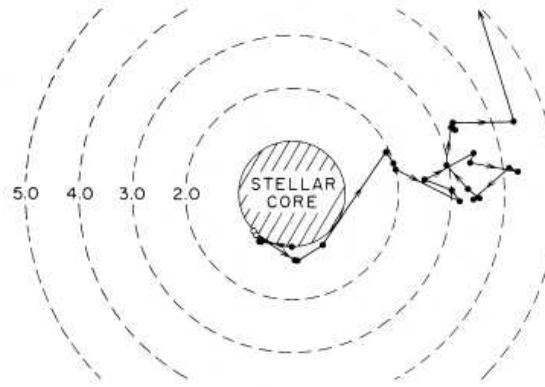


Figure 2. The path of a typical Monte Carlo photon that undergoes multiple interactions with matter on its way through the stellar wind – depositing energy and momentum. Taken from Abbott & Lucy (1985).

multiple line scatterings. This resulted in a more sophisticated formulation of the line acceleration than in CAK. In the original work due to Abbott & Lucy (1985), the ionization calculations were approximated, but subsequent work on combining the MC approach with non-LTE ionization computations (Schaefer & Schmutz 1994, de Koter et al. 1997, Vink et al. 1999) have further improved the method.

The strongest points of the current MC method are the fact that the core-halo approach is dropped, the line force is computed for all radii in photosphere and wind, taking account of the most extensive line lists (H-Zn), ionization stratification, and multiple scatterings on both line and continuum opacity (electron scattering, bound-free and free-free). The main drawback is the fact that the derived mass-loss rates are only *globally* self-consistent, and the momentum equation is usually not solved for, i.e. the mass-loss rates are not locally consistent (but see Vink et al. 1999, Vink 2000).

The basic assumptions that underly all current mass-loss predictions are: (i) stationarity, as hydrodynamic time-dependent line force computations are not yet feasible; (ii) one-fluid, i.e. ion-decoupling is assumed to be negligible; (iii) sphericity, which is probably a rather good approximation for stars at solar Z (Harries et al. 1998), but this may no longer hold for sub-solar Z ; (iv) homogeneity, i.e. the wind is assumed to be smooth. Mass-loss predictions for clumped winds have yet to be performed.

3. Results

Over the last couple of decades the main focus of line-driven wind models concerned the Galactic O supergiant ζ Pup. Comparison between theoretical models and observational data highlighted successes and failures of the theory, which advanced our knowledge of hot-star winds. It is equally important to explore groups of objects, preferentially in different parts of the Hertzsprung-Russell Di-

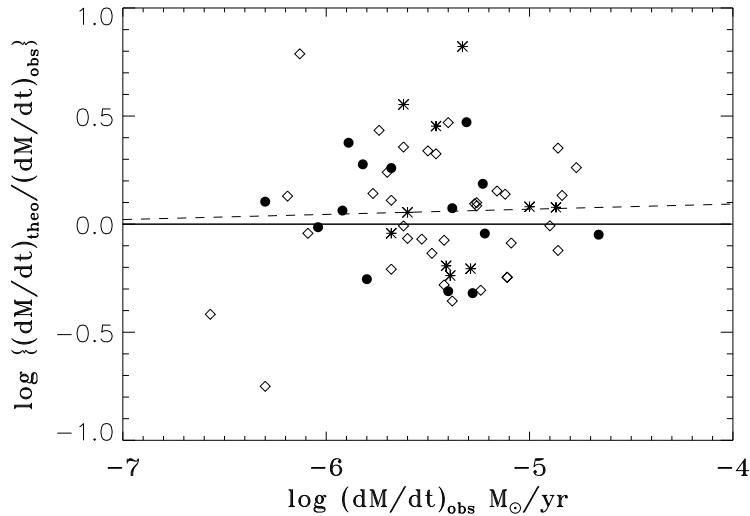


Figure 3. A comparison between Monte Carlo mass-loss predictions from Vink et al. (2000) and a compilation of mass-loss rates – prior to 2000, as a function of the observed mass-loss rate. The comparison shows good average agreement as the scatter is random, i.e. the Monte Carlo method is equally good at predicting weak as dense winds. This figure is taken from Vink (2000).

agram. For this reason, I review below results of wind models for OB stars, LBVs and WRs. For mass-loss determinations of hot low-mass stars as a function of metallicity, see Pauldrach et al. (1988) and Vink & Cassisi (2002).

3.1. OB supergiants at galactic Z

The most used mass-loss predictions for OB supergiants at galactic Z are those from the Monte Carlo simulations by Vink et al. (2000)¹, who find the mass-loss rate of OB supergiants to roughly scale as:

$$\dot{M} \propto L^{2.2} M^{-1.3} T_{\text{eff}}^{-1} (v_{\infty}/v_{\text{esc}})^{-1.3} \quad (4)$$

Equation (4) shows that the mass-loss rate scales strongly with luminosity ($L^{2.2}$), much stronger than the scaling of $\dot{M} \propto L^{1.6}$ often quoted in the literature. The reason is that for the more luminous stars with the denser winds, the MC simulations deliver an increasingly larger mass-loss rate than do the modified-CAK predictions. As the mass-loss rate *also* scales with stellar mass $M^{-1.3}$ (which is often overlooked) and when assuming a typical massive star $M - L$ ratio of $L \propto M^2$, we find an overall \dot{M} scaling with $L^{1.6}$ – in agreement with observational scalings (e.g. Howarth & Prinja 1989). The basic success of the Monte Carlo technique is exemplified in Fig. 3. It shows that properly including multiple scatterings yields equal success for relatively weak winds (with $\log \dot{M} \sim 10^{-7} M_{\odot}\text{yr}^{-1}$) as for dense winds (with $\log \dot{M} \sim 10^{-5} M_{\odot}\text{yr}^{-1}$).

We note that for significantly weaker winds, with $\log \dot{M} < 10^{-7} M_{\odot}\text{yr}^{-1}$, such as the OVz stars, theory and observation appear to show large discrepancies

¹see www.astro.keele.ac.uk/~jsv/

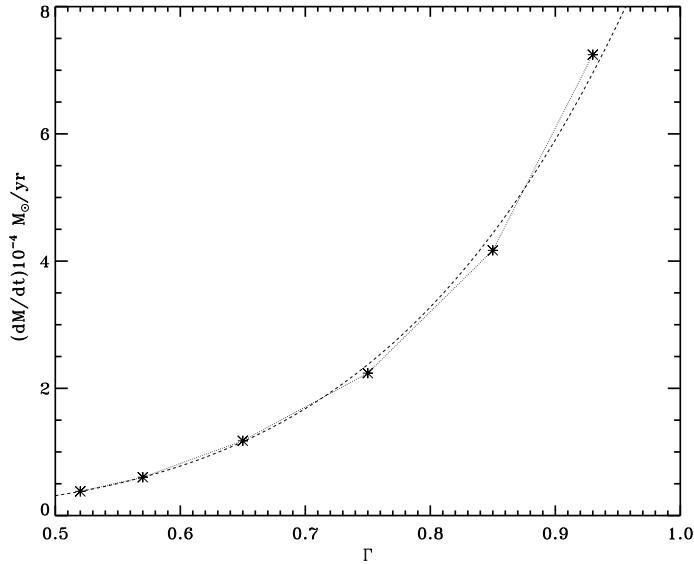


Figure 4. The mass-loss rate of VMS (100 - 300 M_{\odot}) as a function of Γ (in the range 0.5 – 0.9). The dotted line shows that \dot{M} is predicted to increase drastically when approaching the Eddington limit. The dashed line represents $\dot{M} \propto \Gamma^5$.

(Bouret et al. 2003, Martins et al. 2005). In fact, even for denser O star winds, large discrepancies have been reported amongst so-called “reliable” empirical methods (e.g. Fullerton et al. 2005), whilst discrepancies have also been reported for B supergiants (Vink et al. 2000, Crowther et al. 2005, Trundle & Lennon 2005). On the other hand, good agreement between the Vink et al. mass-loss formulae and a variety of other empirical data from radio, $H\alpha$, and UV measurements appears to have been achieved (Benaglia et al. 2001, Repolust et al. 2004, Massey et al 2005). It is clear that despite the success of resolving the wind momentum problem, there are remaining challenges, in particular with respect to our understanding of wind clumping. This may be a vital phenomenon in understanding the source(s) of the reported discrepancies. Resolving these discrepancies is obviously pivotal, as the absolute value of the mass-loss rate is a crucial input for models of the structure and evolution of massive stars.

3.2. LBVs and mass loss close to the Eddington limit

Luminous Blue Variables (LBVs) exhibit growth and shrinking of their stellar radii by factors of ten on timescales of about ten years (Humphreys & Davidson 1994, Weis, these proceedings). Leitherer et al. (1994), Vink & de Koter (2002), and Smith et al. (2004) found that LBVs winds are driven by radiation pressure and that the mass-loss variability can be attributed to changes in the temperature and ionization of the dominant Fe ions. For an explanation of these mass loss changes at these “bi-stability jumps”, I refer the reader to Vink et al. (1999).

Vink & de Koter (2002) found that for LBVs (with $\Gamma (\kappa_e L / 4\pi c g M) \sim 0.5$) the mass-loss rate is strongly dependent on the stellar mass, $\dot{M} \propto M^{1.8}$, a much stronger dependence as for OB supergiants that show $\dot{M} \propto M^{1.3}$.

We may wonder what this implies for objects that find themselves in even closer proximity to the Eddington limit. This is not only relevant for the unstable evolutionary phases of “normal” massive stars, but especially relevant for VMS already from the very beginning of their life.

For this reason, we present preliminary MC mass-loss calculations for VMS in the range $100 - 300 M_\odot$, with $\log(L/L_\odot) 6.3 - 7.0$ (Kudritzki 2002) and Γ in the range of 0.5 – 0.9. The dotted line in Fig. 4 shows that mass loss increases dramatically when approaching the Eddington limit. For comparative purposes, the dashed line represents the function

$$\dot{M} \propto \Gamma^5 \quad (5)$$

3.3. OB winds as a function of Z

Given that radiation pressure on metal lines has been identified to be the driving mechanism for O stars, it follows rather straightforwardly that \dot{M} is smaller at lower Z . Therefore, the question is not so much *if* O star winds are Z -dependent, but rather *by how much*?

Modified CAK predictions over the last decades have predicted that $\dot{M} \propto Z^m$, where m has been found to be between 1/2 and 1 (Abbott 1982, Kudritzki et al. 1987). The first order effect of this scaling is that the CAK k parameter from Eq. (3) – representing the sheer number of lines – is strongly Z -dependent. Second order effects, relating to how α varies with Z , have a particularly strong effect on v_∞ . For a full discussion of how the CAK parameters are expected to vary with Z , see Puls et al. (2000).

Over the years, most stellar evolution models have relied on a square-root dependence of how \dot{M} scales with Z , i.e. $m = 0.5$ (Kudritzki et al. 1987), however I argue that the real dependence is likely to be closer to a linear dependence, $m \geq 0.7$. The difference in the two line-force approaches and the resulting implications for the metallicity slopes are illustrated in Fig. 5 by comparing the modified CAK predictions of Kudritzki (2002), where depth-dependent force multiplier parameters are employed, with the MC predictions of Vink et al. (2001).

As can be seen in Fig. 5, the Vink et al. (2001) predictions show a steeper slope ($m = 0.85$) of the Z -dependence than do the Kudritzki (2002) predictions (where $m = 0.5 - 0.6$). The reasons for this are thought to be the following. CAK-type wind models employ a single line approach, which means that unattenuated stellar flux is offered to each line. This may result in overestimating the mass-loss rate, unless the winds are dense enough so that multiple scatterings are important, and the mass-loss rate is underestimated instead. The single line approach therefore probably leads to a systematic discrepancy between theory and observations, in that the $\dot{M} - L$ dependence is too weak, and the $\dot{M} - Z$ dependence is not steep enough.

On the other hand, most current MC simulations do not solve the momentum equation, and therefore do not account for the dependence of v_∞ with Z . This will likely lead to an overestimate of m , and one should therefore lower

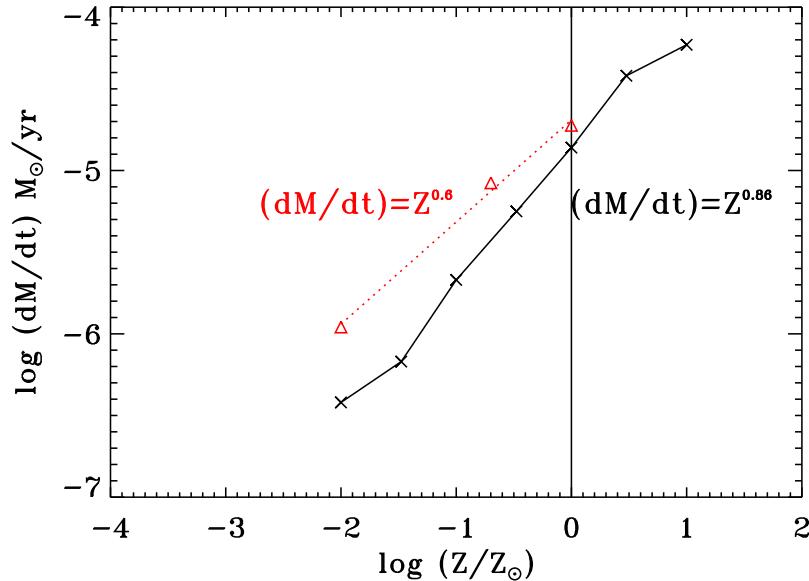


Figure 5. Mass-loss predictions as a function of Z . The solid line indicates the $\dot{M}(Z)$ dependence from MC simulations by Vink et al. (2001). The dotted line is for mass-loss predictions with an updated version of the modified CAK theory due to Kudritzki (2002) for stars in the observable Universe ($\log(Z/Z_{\odot}) \gtrsim 1/100$), for objects with similar stellar parameters. See text for discussion on the difference in slopes.

the m value for O supergiants from 0.85 to 0.7. For these reasons, the use of $m = 0.7$ as the “minimum” value for the mass-loss scaling with Z for O stars is advisable (Vink et al. 2001).

3.4. Wolf-Rayet winds as a function of Z

Unlike the case of OB supergiants, the question of a WR mass-loss versus Z dependence was whether *WR winds scale with Z at all*. This despite empirical indications that WR winds may well depend on the metal content of the host galaxy (Crowther et al. 2002, Hadfield et al. 2005).

Even when it became rather well-established that WR winds are radiatively-driven (Lucy & Abbott 1993, Gayley et al. 1995, Nugis & Lamers 2002, Hillier 2003, Gräfener et al. 2005), the question of a Z -dependence remained highly controversial, with some evolutionary modellers adopting a square-root extrapolation from modified-CAK O-star results, whereas others assumed WR winds not to weaken at lower environmental Z .

The reason often put forward that WR winds might not be Z -dependent is that WR stars *enrich themselves* by burning helium into carbon in their cores. It may be this self-enriched carbon material that would primarily be responsible for the radiative driving, whilst the trace amounts of Fe responsible for driving the OB star winds, would not be important and it should not matter in which galaxy a WR star would reside.

To answer the question of whether WR winds are Z -dependent, Vink & de Koter (2005) performed WR mass-loss predictions at a range of Z , unravelling which elements drive the winds of the WR subtypes, and whether the same

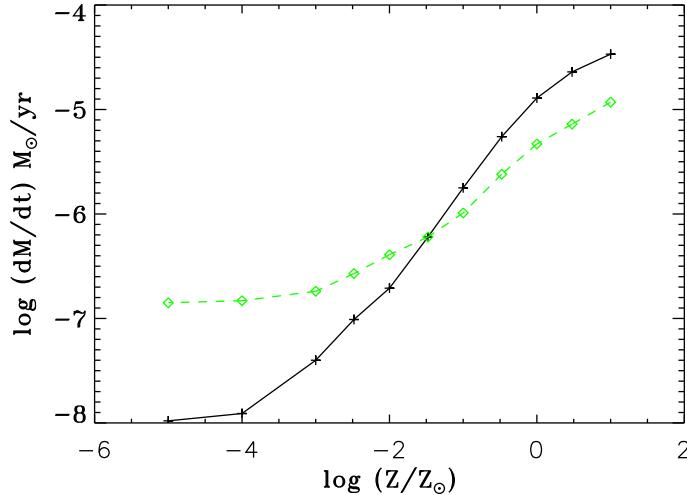


Figure 6. WR mass-loss predictions as a function of Z . The dark line indicates the $\dot{M}(Z)$ dependence for late-type WN stars, whereas the lighter line represents late-type WC star predictions. The slope of the WN models is very similar to OB stars with $m = 0.85$. The slope for WC stars is much smaller, and flattens off below $(Z/Z_\odot) = 10^{-3}$.

chemical species dominate the line force for all Z . Their results are shown in Fig. 6. The dark line denotes the $\dot{M}(Z)$ dependence for late-type WN stars. The slope is identical to that of OB stars: $m = 0.85$, as WN winds are dominated by Fe, and the increase of secondary nitrogen in the photosphere is easily offset by the decrease in carbon and oxygen. These initial results strongly suggest that WN winds should be scaled with Z , with important implications for the final evolutionary phases of massive stars at low Z , such as for black hole formation, supernovae and the determination of the threshold metallicity to form a GRB (Woosley & Heger 2006).

The lighter line in Fig. 6 represents late-type WC wind predictions: the slope is smaller c.f. OB/WN stars. However, it flattens off once the metal content drops below $(Z/Z_\odot) \leq 10^{-3}$, as the ratio of carbon over Fe to the line force increases at lower Z . At solar Z , the large number of Fe lines overwhelms the carbon contribution to the line force near the photosphere, but as Z drops these Fe lines no longer reach the necessary strength (Sobolev optical depth) to be able to contribute to the line force, and carbon takes over.

4. Cosmological implications and future work

It is often commented that mass loss at extremely low ($Z < 10^{-3}$) is negligible because of the rapidly decreasing role of metal-line driving once Z approaches zero. These assertions are based on modified CAK predictions of O stars at low Z (Kudritzki 2002, Krtička, these proceedings). Although it must be true that the line-driving on Fe lines decreases in “normal” ($\Gamma \leq 0.5$) massive stars that we see in galaxies today, I have highlighted two pieces of the jigsaw that are often overlooked: (i) massive stars in close proximity to the Edding-

ton limit (Sect. 3.2.), and (ii) the role of radiation pressure due to carbon via self-enrichment (Sect. 3.4.).

Recent numerical simulations on the formation of Population III indicate that they were both massive and luminous and may well have been in close proximity to the Eddington limit. In addition, there are reasons to believe their rotational surface speeds were larger (e.g. Meynet & Maeder 2004) which may have caused additional mass loss close to the Eddington-Omega limit (Langer 1998). However, this is far from the entire story, as rotation also induces mixing. Due to rotationally-induced mixing of primary nitrogen and carbon (e.g. Meynet et al. 2005, Yoon & Langer 2006) into the atmospheres of zero-metallicity massive stars, the flattening in Fig. 6 suggests that carbon driving may have significantly boosted the mass-loss rates of the first stars, thereby potentially preventing the occurrence of pair-instability supernovae that are believed to occur for initial masses in the range $M = 140 - 260 M_{\odot}$ (Heger et al. 2003), if mass loss from the first stars were negligible.

To start answering these cosmologically important questions, there remains a number of wind aspects to be resolved. As I have mentioned, the MC predictions have achieved a large number of successes, but to be able to confidently predict the mass-loss rates of the first luminous objects, where one cannot rely on direct empirical constraints, a solution of the wind momentum equation is warranted. Furthermore, we need to understand the physics of wind clumping. Hydrodynamical work on wind instabilities and distance-dependent clumping is well underway (e.g. Runacres & Owocki 2002), whereas empirical constraints may be obtained from polarimetric monitoring (see Moffat & Robert 1994 for WR stars, and Nordsieck et al. 2001 and Davies et al. 2005 for the even more strongly clumped winds of LBVs). Once we are able to predict the mass-loss rates and terminal velocities of structured winds from first principles, we can address the questions as to the quantitative role of the winds of the first stars, and whether they could have enriched the IGM – even before the first supernova.

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